THE TIBETAN PLATEAU IN RELATION TO THE VEGETATION OF CHINA

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Vegetation zones of the eastern coast of China represent a series of forests from the tropical to the cold-temperate zone. There is also a change from forest through steppe to desert from the southeastern coast to the northwestern interior (11). These patterns are quite different from those in western Eurasia where the vegetation pattern of the western part from south to north is: tropical, subtropical desert and savanna, Mediterranean sclerophyllous forest, deciduous forest, and coniferous forest. This series shows a pattern, drier in the south and moister in the north, that basically reflects Hadley's classic diagram of atmospheric circulations (10, 25, 26, 28). Therefore, the differences between the eastern and western parts of Eurasia reflect an "asymmetric" distribution of vegetation (Fig. 1). The geographic distribution of vegetation in China-Eastern Asia should be interpreted primarily in terms of patterns of atmospheric circulation in Asia because it reflects the "projection" of atmospheric circulation onto the land surface of the earth.

Recent research in atmospheric physics indicates that the Tibetan Plateau in eastern Asia is a huge "Hot Island" that hinders atmospheric circulation (5). The powerful thermal and orographic effects of the Plateau cause great changes in the atmospheric circulation of the northern hemisphere, especially in Asia, and have a direct effect on patterns of vegetation in that part of the world.

Hereafter I will discuss the uplift of the Plateau in relation to atmospheric circulation and the distribution of vegetation in China. The most important events in this regard are the formation of the Tibetan High, the establishment of the Mongolian anticyclone, and the reinforcement of the Eastern Asian Monsoon.

FORMATION OF THE TIBETAN HIGH AND THE PLATEAU ZONATION OF VEGETATION IN TIBET

The Tibetan High, which arises from the powerful thermal effect of the Plateau in the summer and the cooling effect of the Plateau in the winter, is a vast system of the atmospheric circulation in the upper atmosphere (5) (Figs. 2 and 3). Its center is located in Ali, the western part of the Plateau. This region has very little precipitation—only about 50 mm annually—and is therefore a desert or semidesert climate. Figure 4 shows the extent of the resulting vegetational region. The vegetation is suffrutescent desert and steppe-desert types that are composed mainly of *Ceratoides latens*. In the northwestern part of the Plateau, the climate is very dry and cold by reason of high altitude and its more northern latitude. A sparse high-cold desert of low suffrutescent and cushionlike *Ceratoides compacta* has developed there. On the vast flat of the central Plateau, the annual precipitation increases to about 200 mm, and a high-cold steppe vegetation of *Stipa purpurea* prevails. This is the major vegetation type of the Plateau. In the eastern part of the Plateau there is a cold, low-pressure zone where annual precipitation reaches 600 mm. Under this cold and wet climate, a special kind of high-cold meadow has developed, consisting of *Kobresia* and low scrub *Rhododendron*. Therefore, the Plateau vegetation changes from southeast to northwest, grading from high-cold meadow and scrub through high-cold steppe and desert to high-cold desert. This sere of high-cold vegetation was formed and developed in the Quaternary.

The Tibetan High influences not only the Plateau itself, but is also the center of a great high-pressure belt above Asia, North Africa, and southern Europe. Around the periphery of the Tibetan Plateau, there exist striking differences in climate and vegetation: the southern side of the Plateau is the wet, rainy, and steep slope of the Himalaya Mountains, falling to the India-Bengala plain. In Assam, in the foothills of Eastern Himalayas, the annual rainfall exceeds 10,000 mm, making this one of the rainiest areas in the world. Luxurious tropical mountain forests have developed there. On the opposite, northern side of the Plateau are the Kunlun Mountains. These

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WESTERN FRINGE	CONTINENTAL	INLAND	EASTERN FRINGE
ATLANTIC COAST OF W. EUROPE & N. AFRICA	MID EUROPE - ARABIAN PENINSULA	WESTERN SIBERIA -CENTRAL ASIA- GANGES PLAIN	PACIFIC COAST OF EASTERN ASIA

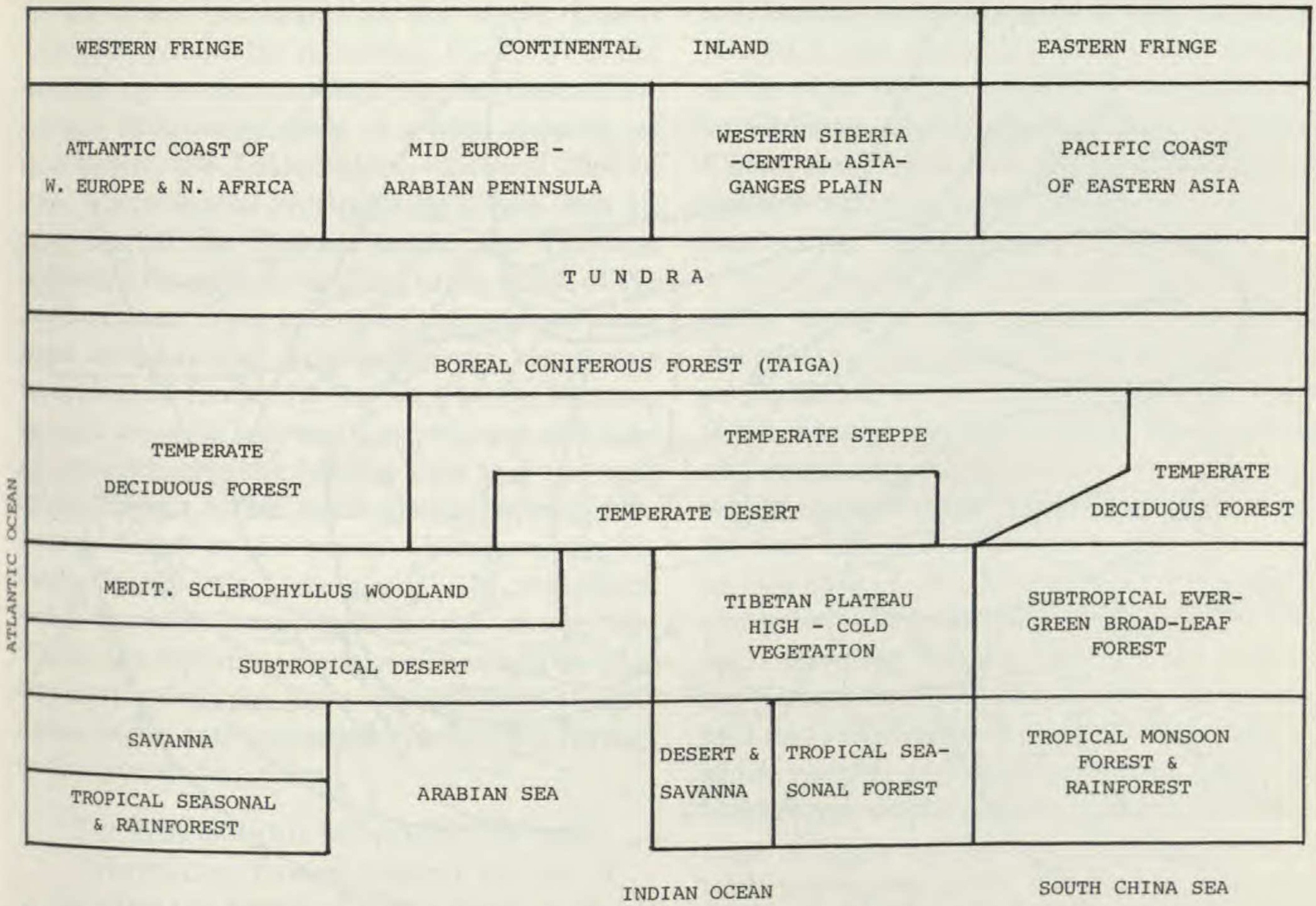

FIGURE 1. Asymmetric distribution of horizontal vegetational zones in Eurasia and North Africa.

FIGURE 2. The summer circulation above East Asia (22).

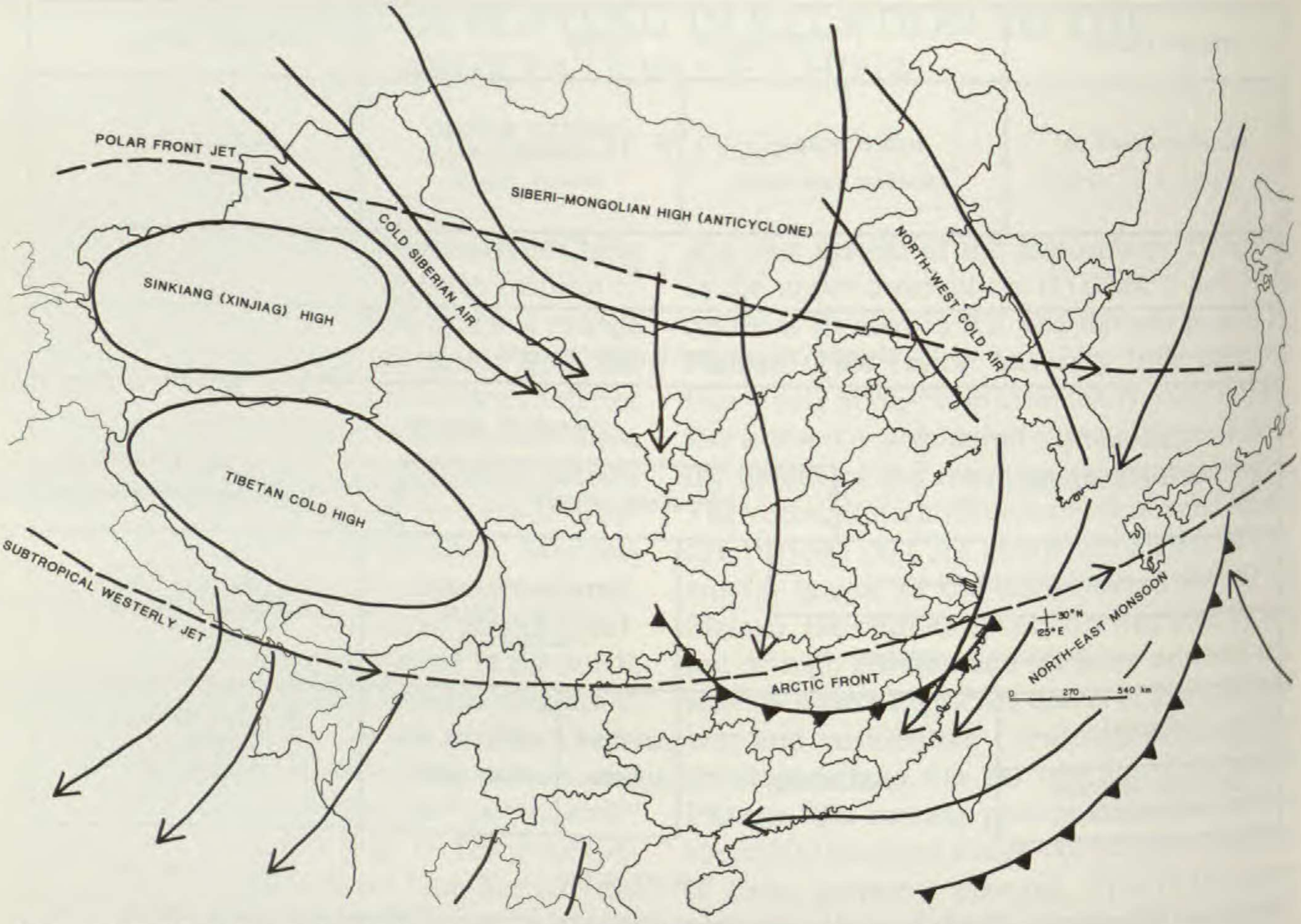

FIGURE 3. The winter circulation above East Asia (22).

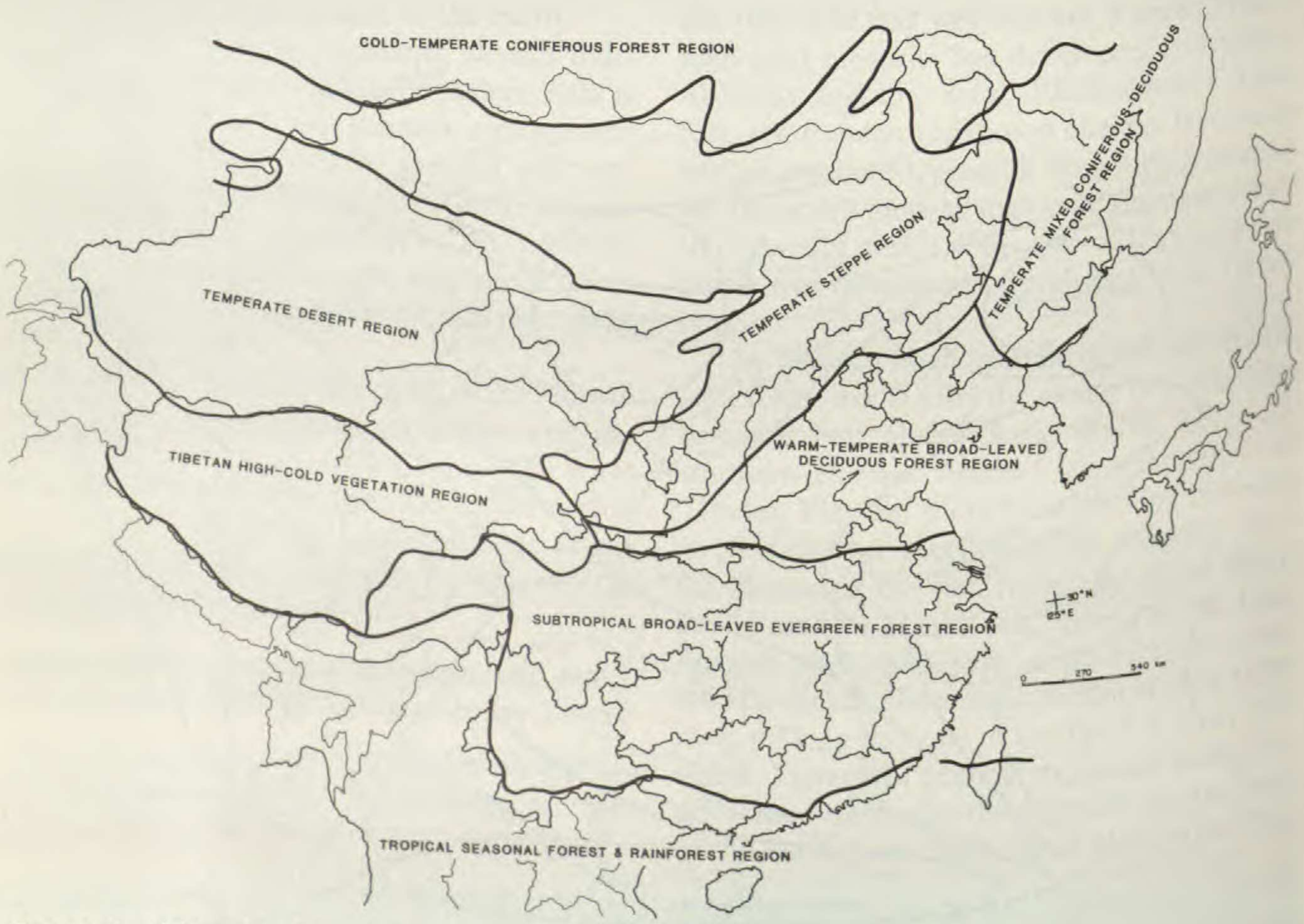

FIGURE 4. The map of vegetational regions of East Asia.

are the driest mountains in the world. Desert vegetation covers the mountain slopes from the foothills up to the snowline. At the base of the Kunlun Mountains there is a vast expanse of sand desert, the Taklamakan—the arid core of Asia, where annual precipitation is less than 10 mm. East of the Plateau, across the Traverse Mountain Range and reaching to the shore of the Pacific Ocean, is an extensive subtropical evergreen broad-leaved and temperate deciduous broad-leaved forest. To the west of the Plateau, through the arid, hot, and desert valley of Kashmir, extending to the Middle East and the west coast of North Africa, is the greatest area of subtropical desert in the world. Therefore, the Tibetan Plateau is a "crossroads" for vegetation and a climatic "watershed divide" in the Old World. The different vegetation zones on the Plateau itself reflect the close connection of the climates, floras, and vegetation types of the Plateau to the surrounding areas.

The Northward Movement of the Westerlies, Establishment of the Mongolian-Siberian Cold High, and Formation of the Desert Vegetation in Central Asia

The Westerlies are located at about 30°N latitude. They represent a system of high pressure circulation that controls the formation of arid zones. Within this zone, the climate is dry, precipitation is rare, the continentality is strong; great sand deserts are found in this zone. The Westerlies form the "desert zone of Cancer" in the tropical and subtropical latitudes. The Tibetan Plateau, which is situated between 30° and 40°N latitude, is a hugh orographic dynamic and thermal hindrance to the Westerlies. The Westerlies divide into southern and northern branches at the western end of the Plateau. In the summer, the northern branch shows an anticyclone curve in northern Sinkiang, situated on the north side of the Plateau. A high pressure zone caused by the compensational descending effect of the Tibetan High occurs above Gansu and Sinkiang. A powerful anticyclonic system—the Mongolian-Siberian Cold High—caused by the Plateau preventing thermal exchange between Siberia and the Indian Ocean, and causing an accumulation of cold air over the continent, is formed in winter. This Mongolian Cold High is the controlling system of the eastern Asian weather during the winter. It makes the winter climate cold, dry, and lacking in precipitation in this area, and has caused a vast temperate desert zone to develop in the plain of Central Asia. It ranges from Iran to Sinkiang, Gansu, Qinhai, Inner Mongolia of China, and Western Mongolia. Its northern limit reaches nearly to 50°N latitude; far beyond the limit of the "desert zone of Cancer."

According to computer simulations by Manaba, the great high pressure system was produced over continental Siberia on the north side of the Plateau only after the Plateau was uplifted. If the Plateau were eliminated, the desert areas of Central Asia would have a moist climate that would support forest or grassland vegetation and the wet, hot, and fertile plain of India would be an arid zone (4, 21). Research in Chinese geology and paleobotany has also established the following: before the Tibetan Plateau had arisen and the Tethys Sea had disappeared, there was an arid and hot climate in central China, but it was much warmer and moister in Dzungaria, which had a forest-steppe climate and vegetation at that time. After the uplift of the Plateau and the westward movement of the Tethys Sea, the climate in central China became moist, and in northern China the climate changed from warm and moist to cold and dry. The northwestern part of China became a temperate desert (7). The formation of deserts proceeded with uplift of the Plateau and moved gradually northward (4).

The Plateau prevents the effects of marine monsoons reaching the Central Asian desert region. Only a remnant of the Southwestern Monsoon reaches the Alasan and Hexi Corridor in the summertime, and then causes a concentration of precipitation. Therefore, there have developed some annual summer ombrophiles in the flora that are characteristic of the eastern Central Asian desert. Dzungaria is located in the western part of Central Asia and receives some of the Mediterranean subtropical air masses. This causes more spring rainfall and has led to development of a vegetation containing spring-ombrophiles, which are characteristic of the western Central Asian desert. The Beishan Gobi, East Sinkiang, and the eastern part of South Sinkiang are located in the most arid core of the desert, and are under the influence of the center of high pressure and powerful anticyclone. There is very little precipitation, usually not more than 10 mm. The desert vegetation is sparse, and there often appear vast bare areas of the "Gobi," drift sand, and "Yardang."

EXPANSION OF THE STEPPE VEGETATION AND COMPRESSION OF THE DECIDUOUS BROAD-LEAF FOREST BY THE EFFECT OF THE MONGOLIAN COLD HIGH

There is no significant orographic hindrance to atmospheric circulation in the eastern part of Asia. Therefore, the cold Mongolian-Siberian anticyclone caused by the uplift of the Tibetan Plateau invades southward in Eastern Asia. This has permitted steppe vegetation, which is adapted to arid and cold continental climate, to expand southeastward. This has restricted the area of the mesic deciduous broad-leaf forest, which requires a temperate, moist climate. Several thousand years of agricultural activity have destroyed the primeval forest vegetation in the central plains of China (the Yellow River Basin), one of the original centers of ancient culture, and accelerated the development of the steppe. Generally, the area of broad-leaved deciduous forest in eastern Asia is more limited and smaller than that in Western Europe and North America. It disappears abruptly in the central part of eastern Asia. The spring drought and the cold winter that are caused by the Mongolian High are the most important limiting conditions for development of broad-leaved deciduous forest in eastern Asia.

The temperate steppe zone, which crosses the center of Eurasia, bends southward in eastern Asia and reaches it southern limit at 34°N latitude, a large southward deviation. The eastern Asian steppe zone is transitional between the arid-cold climate controlled by the Mongolian-Siberian High and the moist climate under the influence of the eastern Asian Monsoon Low. The steppe zone can be divided into three transitional subzones: the desert-steppe, the typical steppe, and the forest-steppe. Communities in these subzones are dominated by various steppe grasses. The subzones conspicuously reflect the transition from arid to semi-moist climate, and from desert to forest vegetation.

ALEUTIAN LOW AND PRESENCE OF THE NORTHEASTERN MIXED NEEDLE-BROAD-LEAF FOREST

A temperate, mixed, needle-broad-leaved forest type is distributed in the northeastern part of eastern Asia (Northeast China, North Korea, and the Soviet Far East). Its dominant, Korean pine (*Pinus koriensis*), requires a moist maritime climate. The persistence of this mesic forest type might be under the influence of the Taiwanese warm current—the Black Tidal Current, which passes by the coast of northeastern Asia, creating a moist and rainy climate (27). In terms of atmospheric circulation, eastern Asia is mainly under the control of the Aleutian Low in the winter, and transitional between the hot Tibetan Plateau and the cold Okhotsk Sea in the summer. The northern limit of the effect of the warm-humid Eastern Monsoon, which produces abundant precipitation, is in this region. Therefore, eastern China is more moist than northern China, and serious droughts are rare.

According to the research of Kasahara and Asakura (21), if the Tibetan Plateau were not present, the Aleutian Low and the Okhotsk High might not form or might be unstable. It might be, then, that the Plateau affects the distribution of the northeastern mixed needle-broad-leaved forest.

Not more than 500 km from the coast, the maritime climate is replaced by a continental climate controlled by the Mongolian High, and the mesic mixed forest disappears. Beyond the taiga of the Great Xingan Mountains, the vegetation rapidly becomes steppe.

PREVALENCE OF THE EASTERN MONSOONS AND DEVELOPMENT OF THE BROAD-LEAVED EVERGREEN FOREST

The subtropical climate of southern and southeastern Asia is controlled chiefly by the hot low-pressure system of the Southeastern and Southwestern Monsoons in the summer. In the winter it is influenced strongly by the Mongolian Cold High. In this region monsoons are more strongly developed than elsewhere and are mostly a result of the presence of the Tibetan Plateau. The effects of the Plateau are:

The importance of the Southwestern Monsoon (21). There is a branch of the humid Southeastern Monsoon that comes from the Indian Ocean, passes over the mountains of western Yunnan and Burma, and blows into continental Eastern Asia in summer. It converges with the northwestern current at 30–36°N latitude, and produces abundant summer rainfall and the "Plum rains" in the Yangtze-Huai River Basin. This precipitation is an important water supply for the southern and southeastern Asian subtropical broad-leaved evergreen forest.

The stabilization and reinforcement of the Southeastern Monsoon. The restriction on the Westerlies and the thermal effect of the Plateau increases and maintains the stability and intensity of the monsoons in Eastern Asia. This permits the monsoons to reach to both northerly

and southerly extremes (15, 16). The reinforced summer monsoons bring abundant rainfall, which is a major factor for the development of the southern and southeastern Asian broad-leaved evergreen forest.

The tropical cyclone. Typhoons also have an important effect of increasing the water supply for the eastern Asian broad-leaved evergreen forest. The Tibetan High is a strong influence in turning typhoons northward.

The southwestern low vortex. This powerful vortex forms on the plateau and moves eastward in the summer. It is an important weather system, producing summer rainstorms in eastern Asia.

Therefore, the Tibetan Plateau is an orographic and thermal factor that maintains, reinforces, and even forms the eastern Asian Monsoons and other weather systems. Its effects are indispensable for the development of the southern and southeastern Asian subtropical broad-leaved evergreen forest. The savanna or thorn scrubs of subtropical desert do not develop in a monsoon climate. Only a few relicts of these types of vegetation are present in rain shadows of the dry and hot valleys of the Traverse Mountain Range, where there is a hot low-pressure system formed by the descent and convergence of the Westerlies.

Establishment of the Tropical Easterlies and Distribution of the Tropical Rainforest and Monsoon Forest in Southeastern Asia

The powerful Easterlies, which occur south of 20°N latitude in southeastern Asia, India, and North Africa in the summer, are one of the high-level circulation systems that control the climate of these tropical areas (19). They are supported by the Tibetan High and Saharan High (23) and are especially prevalent at the south edge of the Tibetan Plateau. Some meteorologists emphasize that the Tibetan High affects the presence of the Easterlies, suggesting even that the Plateau was the basic cause of their establishment (22, 24). The Easterlies bring abundant rainfall into southern Asia and are the major supplier of water to the tropical forests in this area. Where they cease in winter, the dry season of such tropical areas, the tropical deciduous forest enters dormancy. In North Africa and the Middle East, there is a powerful descending air-flow on the southern side of the Easterlies, causing a vast area of tropical desert.

The Southwestern Monsoon, caused by the uplift of the Plateau, has had an important effect on the development of the tropical rainforest in the southwestern part of tropical China, India, and the Peninsula of Middle South. The warm, humid air of the Monsoon comes from low altitudes over the Indian Ocean and blows into Bengala and the eastern Himalayas. It is transformed into a cyclone curve by the horseshoe-shape of the mountain barrier, and produces abundant rainfall in the mountains. The annual precipitation of 5,000 to 10,000 m maintains luxuriant montane tropical rainforests and seasonal semi-evergreen forest. Because of the orographic and humid-hot monsoon effects, the tropical montane forests reach their northernmost limit here at 29°N latitude. The tropical seasonal forests of Xishuangbanna in Yunnan are also supported mainly by the Southwestern Monsoon. However, as the cyclonic winds of the eastern Himalayas turn westward and become an east wind along the southern foothills of the Himalayas into Punjab, the rainfall decreases significantly westward and the dry season becomes more severe. Thus, there are no rainforests on the southern foothills of the central Himalaya Mountains. Instead, there are monsoon forests that are mainly composed of the deciduous *Shorea robusta.*

Additionally, the Tibetan Plateau becomes a hindrance in the western part of Eastern Asia in the invasion of the Siberian cold current in the winter. This is an important reason for the northward deviation of the limit of tropical vegetation there. Because of this obstruction, the Yunnan Plateau, the eastern Himalayas, and the Indian Peninsula are rarely invaded by cold currents. The temperature in the winter there is higher than that further east. Because the eastern plain of China lacks the protection of high mountains, the cold current from the Mongolian Cold High can reach to the far south, producing cold waves in the southeastern subtropical and tropical zones, leading to cold injury of rubber trees, bananas, and other tropical crops, and pushing the tropical limit southward to the Tropic of Cancer. Therefore, the northern limit of tropical vegetation in China reaches higher latitudes in the west than in the east.

Conclusions

Neogene-Quaternary uplift of the Tibetan Plateau greatly changed and fragmented the zonal vegetation pattern that would have otherwise prevailed in much of eastern Asia. The major expressions of these changes are: the formation of the high-cold plateau vegetation zones; the

northward extension of the subtropical desert zone and formation of temperate desert in Central Asia; the expansion of the temperate steppe zone to the east and south; the restriction of broad-leaved deciduous forests; the preservation of the mixed needle-broad-leaved forest in northeastern Asia; the reinforcement of the eastern Asian Monsoon region causing an expanded development of the south and southeast Asian subtropical broad-leaved evergreen forest, instead of subtropical savanna and desert there; and the modified northern limit of the tropical forest zone in parts of southern Asia. These features of vegetation zonation, all the result of the uplift of the Tibetan Plateau, are unique to Eastern Asia.

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